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(54) Radar antenna system

(57) A radar antenna system comprises a circular array of column radiators (11) and monopulse means (14,16, 21, 22, 23) for transmitting and receiving signals on cyclically selected sets of the radiators, each set having a plurality of selectable different look directions. The azimuth of a target is given by the algebraic sum of the particular look direction of the radiator set receiving the reply and the deviation from that look direction determined by the monopulse means. With monopulse, azimuth determinations become more inaccurate the larger the deviation from the look direction. To enhance the accuracy and the resolution obtainable from discrete look direction, the system further comprises means (30) for averaging a plurality of azimuth determinations of the same target made in different look directions. The azimuths in the average are weighted with increasing importance being attributed to determinations the smaller their deviation from the particular look direction of the radiator set which received the reply.

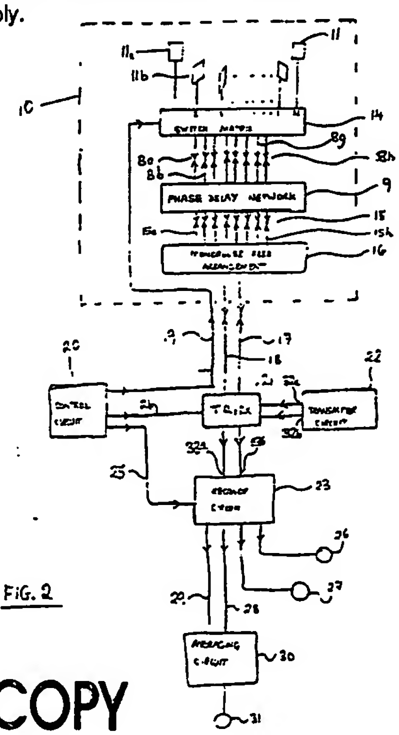

FIG. 2

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RADAR ANTENNA SYSTEM

The present invention relates to a radar antenna system especially, but not exclusively, for use in a ground installation for a secondary radar system.

Such a ground installation requires an antenna capable of scanning in azimuth. In a common arrangement, a directional antenna of substantial size is employed. The antenna is mounted on a purpose built tower which has a rotatable assembly to enable the antenna to be rotated for radar scanning in azimuth.

Difficulties exist in siting the tower clear of buildings and runways and the antenna is commonly at a remote location, requiring expensive cabling to the control tower. The rotating antenna is too massive to be mounted conveniently on the control tower or other terminal building. Problems with noise and vibration would also be encountered were a rotating antenna to be mounted on the control tower, or other terminal building.

The object of the present invention is to provide an antenna system which can be of substantially lighter and more compact construction and which is nevertheless capable of adequate resolution in azimuth, at a lower cost than the known techniques.

According to the present invention, there is provided a radar antenna system comprising an array of radiators, means for selecting different sets of the radiators, the different sets having different look directions, means for exciting a selected set of the radiators, monopulse means for receiving replies on a selected set of the radiators, whereby the azimuth of a target is given by the algebraic sum of the particular look direction of the radiator set receiving a reply and the deviation from that look direction determined by the monopulse means, and means for averaging a plurality of results of replies received from the same target in different look directions so as to enhance the accuracy of determination of the azimuth of the target.

Such an antenna does not need to be physically rotated to achieve scanning in different directions, and hence may be operated without causing problems from mechanical noise and vibration through

its support. The antenna can be light enough to be fixed to a static portion of a suitable tower such as the control tower itself.

In a preferred form, the average azimuth is determined as a weighted average with the weights attributed to replies decreasing the greater the magnitude of the deviation from the look direction of the radiator set on which a reply is received. Such a process of averaging permits the effects of known inaccuracies characteristic of monopulse systems to be reduced.

An embodiment of the invention will now be described by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a perspective view from below of a mast antenna of a radar antenna system embodying the invention;

Figure 2 is a block diagram of the radar antenna system; and

Figure 3 is a diagram illustrating operation of the antenna system.

Referring to Figure 1, an antenna 10 comprises column radiators 11 arranged radially in a ring, and supported by a frame 12 fixed to a mast 13. The number of column radiators 11 in the ring may be thirty two. Column radiators are well known in themselves and are in commercial use, e.g. in linear array antennas used in secondary radar.

Referring to Figures 1 and 2, the frame 12 includes a lower ring 12a within which is arranged a switch matrix 14, a phase delay network 9, and a monopulse feed arrangement 16 to feed the column radiators. The monopulse feed arrangement 16 has eight feed terminals 15a to 15h which are connected through the phase delay network 9 to eight corresponding terminals, 8a to 8h respectively, of the switch-matrix 14. The terminals 8 can be connected through the switch matrix 14 to a selected set of adjacent column radiators 11. By means of the switch matrix 14, any of the thirty-two different such sets can be selected at will, each of which has a different azimuthal look direction axis. The terminals 8 can be connected to the radiators 11 of a selected set in a certain order, such that, for example, the first terminal 8a is connected to the first radiator 11a of the set, and the second terminal 8b is connected to the second radiator 11b, with similar connections for the remaining terminals 8c to 8h. Alternatively, the terminals 8

may be connected in reverse order, such that, for example, the eighth terminal 8h is now connected to the first radiator 11a, the seventh terminal 8g is connected to the second radiator 11b, and the other connections are similarly reversed in order.

The phase delay network 9 is known in itself, and is in commercial use in aerial arrays. It introduces predetermined relative phase differences into the eight feed signals fed to or from the column radiators 11 through the switch matrix 14, such that a phase delay taper is produced across the feed signals. The phase delay taper has the effect of causing the actual look direction of a selected radiator set to be offset azimuthally to one side of the axis of the set. Reversing the order of the connections to the radiators, as hereinbefore described, reverses the direction of the phase taper delay, and hence causes the look direction to be offset azimuthally to the opposite side of the axis. Thus by suitable switching of the switch matrix 14, a possible 64 different look directions, or beam boresights can be obtained. It is arranged that these 64 look directions are uniformly spaced around the azimuth. Thus the axes of the 32 sets of radiators are spaced at intervals of 11.25° and the phase taper introduced by the network 9 introduces an offset or squirt of 2.8125°.

A control circuit 20 determines which direction of phase delay taper and which set of radiators are selected by the switch matrix 14, depending on a desired look direction. Control signals are communicated from the control circuit 20 to the switch matrix 14 by means of a first control feed 19.

The monopulse feed arrangement 16 is known in itself, and is in commercial use in secondary radar systems. It comprises sum and different networks which reduce signals at the eight terminals 15 to a net sum signal in a sum channel 17, and to a net difference signal in a difference channel 18. Conversely, signals fed into the monopulse feed arrangement 16 through the sum channel 17 and the difference channel 18 are processed into reciprocal sum and difference signals which appear at the eight terminals 15. The order of connection of the terminals 8 through the matrix 14 will affect the sense of the difference signal, in that reversing the order of the connections causes the difference signal to be negated,

or inverted. However, under control of the control circuit 20, other parts of the system can be operated to take account of the sense of the difference signal depending on the look direction selected.

Three connectors are provided on the lower ring 12a for connecting the antenna 10 to the rest of the radar system, namely an R.F. first connector 17a for the sum channel 17, an R.F. second connector 18a for the difference channel 18, and a third connector 19a for the first control feed 19.

Referring now to Figure 2, the sum channel 17 and the difference channel 18 are each connected through a transmit/receive switch 21 to either a transmitter circuit 22 or a monopulse receiver circuit 23. The position of the switch 21 is controlled by the control circuit 20, communicating with the switch 21 by means of a second control feed 24.

The transmitter 22 has a main output 32a for transmitting radar interrogation signals through the sum channel 17, and a control output 32b for transmitting control pattern signals through the difference channel 18. A conventional secondary radar interrogation transmission comprises a sequence of three signal pulses, namely a first signal pulse from the main output 32a, a second signal pulse from the control output 32b, and a third signal pulse from the main output 32a. In the transmit mode, these signals are fed to the monopulse feed arrangement 16 and phase delay network 9, and directed through the switch matrix 14 to be transmitted in a certain look direction by a selected set of column radiators 11.

The monopulse receiver 23 has conventional sum and difference inputs, 33a and 33b respectively, for determining the azimuth of signals received from a target. In the receive mode, signals received from a certain look direction by a selected set of radiators 11 are connected through the switch matrix 14 to the monopulse feed arrangement 16. The received signals are there reduced to sum and difference signals in the sum and difference channels 17 and 18 respectively, and fed to the respective inputs of the monopulse receiver 23. The monopulse receiver determines the azimuthal deviation of the target direction from the look direction boresight by measurement of the relative signal strengths in the sum

and difference channels. A common technique for achieving this measurement employs sum and difference inputs 33a and 33b respectively which have a logarithmic characteristic. The ratio of the signals can then be obtained by subtracting the two input channels. The subtraction may be performed digitally in the receiver after having first converted the logarithmic signals into digital form. The azimuthal direction of the received signals is determined from the algebraic sum of the measured azimuthal deviation and the known azimuthal look direction, the latter being communicated to the receiver 23 by a third control feed 25 from the control circuit 20. The receiver 23 has an output 28 representative of the determined azimuthal deviation from the look direction, and an output 29 representative of the azimuthal direction calculated above. The outputs 28 and 29 are fed to an averaging circuit 30, whose operation is described hereinafter.

The receiver 23 includes a circuit for determining the range of the reply signals by measurement of the elapsed time interval between a radar interrogation signal transmission, and a received reply. The determined range appears as an output 26.

The receiver 23 also includes a circuit for decoding information, such as elevation or identity, which may be encoded by a target in its reply signal. The decoded information appears as an output 27.

In operation, the control circuit 20 controls the switch matrix 14 to cyclically select different sets of radiators, thereby scanning the look direction of the radar. In each position of the switch matrix 14, the monopulse transmitter 22 sends radar interrogation pulses which are transmitted a the respective look direction of the selected radiators 11. The switch matrix 14 dwells on the respective look direction for as long as is necessary to enable any reply which may be forthcoming to be received. Such replies are processed by the monopulse receiver 23, as described hereinbefore.

For each target identified, the averaging circuit 30 computes an average of the azimuth determined from beams in different look directions to increase the accuracy of the radar system. As illustrated hereinafter, a measurement of the azimuth of the target

made in a look direction from which the azimuthal deviation of the target direction is small is more accurate than a measurement made in a look direction from which the azimuthal deviation is large. Each azimuth in the average is therefore weighted, with increasing importance being attributed to determined azimuths the smaller their deviation from the respective look direction of the radiators selected at the time the respective reply was received. The averaged azimuth of the target appears as an output 31 from the averaging circuit 30.

For the purpose of illustration, a comparison will now be described showing the effect of the weighted averaging of azimuth measurements of a target made in two adjacent look directions, compared with the equivalent measurement made in only one of the above directions.

Referring to Figure 3, a target 34 is located at a distance from the antenna 10. The azimuth of the target 34 lies between certain first and second look directions, or beams, whose azimuthal bearings from North are 33.75^{o} and 39.375^{o} respectively. It is to be noted that with the antenna described above having sixty-four uniformly distributed possible look directions, adjacent look directions are separated by 5.625^{o} and that a measured deviation from a certain look direction of 5.625^{o} should correspond to a measured deviation from one adjacent look direction of 0^{o}.

The effect of i.f. amplifier errors in a monopulse receiver is to make the measured angle closer to, or further from, boresight than the true value. Since the antenna beams are switched, and not continuously rotating, the target will tend to remain in a constant position in an antenna beam for some period of time. The bearing error takes the form of a bias error which is dependent upon the position of the aircraft in the beam.

The receiver errors which contribute to a bias error are as follows:

Sum channel error	±0.314 dB
Difference channel error	±0.314 dB
Frequency error	±0.314 dB
Antenna calibration error	±0.314 dB
Total	±1.256 dB

Table 1 is a table of bearing errors based on a worst case assumption of all the errors occurring simultaneously to provide a total error of 1.256 dB:

Table 1 Worst case bearing errors

Angle from boresight (degs)	Sum-Diff ratio (dB)	Sum-Diff error (dB)	Bearing error (degs)
0	30.0	0.0	0.00
1	22.5	1.3	0.17
2	16.5	1.3	0.29
3	12.9	1.3	0.43
4	10.5	1.3	0.55
5	8.5	1.3	0.70
6	6.8	1.3	0.74
7	5.2	1.3	0.79
8	4.0	1.3	0.90
9	2.7	1.3	0.97
10	1.4	1.3	0.05
11	0.4	1.3	0.14

From the above table it can be seen that bearing measurements made close to a beam centre are the most accurate. Any measurement made further away from a beam centre than 3 degrees (strictly speaking 2.8125 degrees) would be closer to the beam centre of the adjacent beam which would give better accuracy. Table 4

below summarises the bearing measurement error and column five shows this error when the optimum beam is used.

A given amplifier amplitude error which, say exaggerated the sum-difference signal ratios, would make the target 34 appear at a smaller angle from beam, centre than is the true case. However the same error would make the target appear closer to the beam centre of the adjacent beam. Replies from the same target can be obtained in two adjacent antenna beams and the bearing measurements made on these separate replies averaged, thereby compensating for some of the bias errors.

In averaging bearing measurements made on two adjacent beams, weight should be given to the measurement made in the more accurate position. The following formula is used:

$$[(D_1 \times S_1) + (D'_2 \times S_2)]/(S_1 + S_2)$$

where

D_1 = azimuthal deviation of target from beam 1 look direction

S_1 = beam 1 slope at deviation D_1

D'_2 = azimuthal deviation of target from beam 2 look direction re-referenced to beam 1 look direction

S_2 = beam 2 slope at azimuthal deviation of target from beam 2

Beam slopes for use in the above formula are the sum-difference pattern slopes set out in Table 2:

Table 2 Sum and different pattern slopes

Angle from boresight (degrees)	Pattern Slope (dBs per degree) Sum	Difference	Sum-Diff
0	0.0	infinity	-infinity
1	-0.2	7.4	-7.6
2	-0.2	4.2	-4.4
3	-0.3	2.6	-2.9
4	-0.3	2.0	-2.3
5	-0.4	1.4	-1.8
6	-0.5	1.2	-1.7
7	-0.6	1.0	-1.6
8	-0.6	0.8	-1.4
9	-0.7	0.6	-1.3
10	-0.7	0.5	-1.2
11	-0.8	0.3	-1.1

An example will make the weighting equation above clear. Assume that beam 1 detects the target 34 at $+ 1^{o}$ relative to its look direction and beam 2 detects the same target at -5^{o} relative to its look direction, that is at $+0.625^{o}$ relatived to the first beam look direction. $D_1 = 1^{o}$ and $D'_2 = 0.625^{o}$. From Table 2 the beam slope at 1^{o} deviation from beam look direction is $S_1 = -7.6$. The beam slope at 5^{o} deviation from beam look direction is $S_2 = -1.8$. The weighted azimuthal deviation from the beam 1 look direction is thus:

$$(1^{o} \times -7.6) + (0.625^{o} \times -1.8)/(-7.6 -1.8) = 0.928^{o}$$

If all the receiver amplitude errors of the second beam were identical to those affecting the measurements made with the first beam then the errors would be completely cancelled by averaging between the two beams. Such a result is unrealistically optimistic.

However, a number of error sources are consistent between beams and are cancelled by averaging:

Over the $\pm$ 6 degrees of antenna beam of interest, the

sum channel signal strength remains approximately constant and the amplitude errors in this channel compensate.

The transponder is the same and the frequency-dependent errors are the same in both beams and compensate.

At an angle of 3 degrees from boresight, the difference signal amplitudes in the difference channel are equal and compensate.

In order for the weighted average of measurements made in two adjacent beams not to cancel all bearing errors, it is necessary to identify the errors which are unequal in the two beams. These errors are:

The calibration error of the two beams.

The difference channel amplitude error except at 3 degrees from boresight where they must be equal.

In Table 3 the antenna calibration error is assumed to be in the opposite sense to that assumed in Table 1 in order to maximise the difference. Similarly the difference channel error is assumed to be in the opposite sense except at 3 degrees where it must be the same.

Table 3 Worst case bearing errors for beam 2

Angle from boresight (degs)	Sum-Diff ratio (dB)	Sum-Diff error (dB)	Bearing error (degs)
0	30.0	0.0	0.00
1	22.5	0.6	0.08
2	16.5	0.6	0.14
3	12.9	0.9	0.32
4	10.5	0.6	0.27
5	8.5	0.6	0.35
6	6.8	0.6	0.37
7	5.2	0.6	0.39
8	4.0	0.6	0.45
9	2.7	0.6	0.48
10	1.4	0.6	1.52
11	0.4	0.6	1.57

The following table shows the improvement obtained by weighted averaging (right hand column):

Table 4 Optimum bearing error (single reply) and weighted bearing error (average of replies in adjacent beams)

--------Beam 1--------		--------Beam 2--------		Optimum	Weighted
Angle from boresight (degs)	Bearing error (degs)	Angle from boresight (degs)	Bearing error (degs)	Bearing error (degs)	Bearing error (degs)
0	0.00	-6	0.37	0.00	0.00
1	0.17	-5	0.35	0.17	0.07
2	0.29	-4	0.27	0.29	0.10
3	0.43	-3	0.32	0.43	0.06
4	0.55	-2	0.14	0.14	0.10
5	0.70	-1	0.08	0.08	0.07
6	0.74	-0	0.00	0.00	0.00
7					
8					
9		Use Beams 2 and 3			
10					
11					

With a radar system in accordance with the invention, the look direction can also be switched rapidly to random azimuths, and could support a Mode S data link role since the dwell time is not limited. In one possible application at an airport, this would allow multiple segment Comm-C and Comm-D messages to be transferred between ground and air without the need for high duty-cycle transmitters.

When used with an SSR system the antenna would be receiving several replies on each scan. These replies can be equally divided between one beam and its adjacent beam and bearing measurements made using the two beams averaged.

In a Mode S data link role, where multiple Comm-B or Comm-D replies were received, two adjacent beams could also be used and the separate bearing measurements averaged.

In the case of a single reply Mode S Surveillance, Comm-B or

Comm-D the averaging between separate replies is not possible. However consideration could be given to receiving the preamble in one beam and the data block in an adjacent beam, with separate bearing measurements made on each so that averaging can be employed to improve accuracy.

It will be appreciated that with an antenna in accordance with the invention, there is no need to employ a special tower or mast having a rotating joint for scanning in azimuth. The antenna may be fixed to a static portion of a suitable tower. It will also be appreciated that the antenna described in the preferred embodiment has a low windage compared with that of larger radar antennas, thereby allowing the use of less sturdy supports. The antenna may also be compact and light enough to permit it to be mounted on the control tower at an airport, or on other terminal buildings.

CLAIMS:

1. A radar antenna system comprising an array of radiators, means for selecting different sets of the radiators, the different sets having different look directions, means for exciting a selected set of the radiators, monopulse means for receiving replies on a selected set of the radiators, whereby the azimuth of a target is given by the algebraic sum of the particular look direction of the radiator set receiving a reply and the deviation from that look direction determined by the monopulse means, and means for averaging a plurality of results of replies received from the same target in different look directions so as to enhance the accuracy of determination of the azimuth of the target.

2. A radar antenna system according to claim 1, wherein the average is a weighted average with the weights attributed to replies decreasing the greater the magnitude of the deviation from the look direction of the radiator set on which a reply is received.

3. A radar antenna system according to claim 1 or 2, wherein the sets of the radiators are selected cyclically for radar scanning.

4. A radar antenna system according to claim 1 or 2, wherein the radiators are a ring of column radiators.

5. A radar antenna system according to claim 1, 2, 3 or 4, comprising a single monopulse feed network and a switching matrix for connecting this network to the different sets of radiators.

6. A radar antenna system according to any of the preceding claims, wherein there are thirty two radiators in the array.

7. A radar antenna system according to claim 6, wherein there are thirty two sets of radiators, each set comprising eight adjacent radiators.

8. A radar antenna system according to any of the preceding claims, further comprising means for producing a plurality of selectable different look directions for each set of radiators.

9. A radar antenna system according to claim 8, wherein the means comprise a network for selectively introducing predetermined relative phase differences in the signals exciting or being received on the radiators in each set, such that a phase delay taper is introduced across the set of radiators.

10. A radar antenna system according to any of the preceding claims, wherein there are sixty four different look directions.

11. A radar antenna system according to any of the preceding claims, adapted to be mounted on an airport building.

12. A radar antenna system substantially as hereinbefore described with reference to the accompanying drawings.

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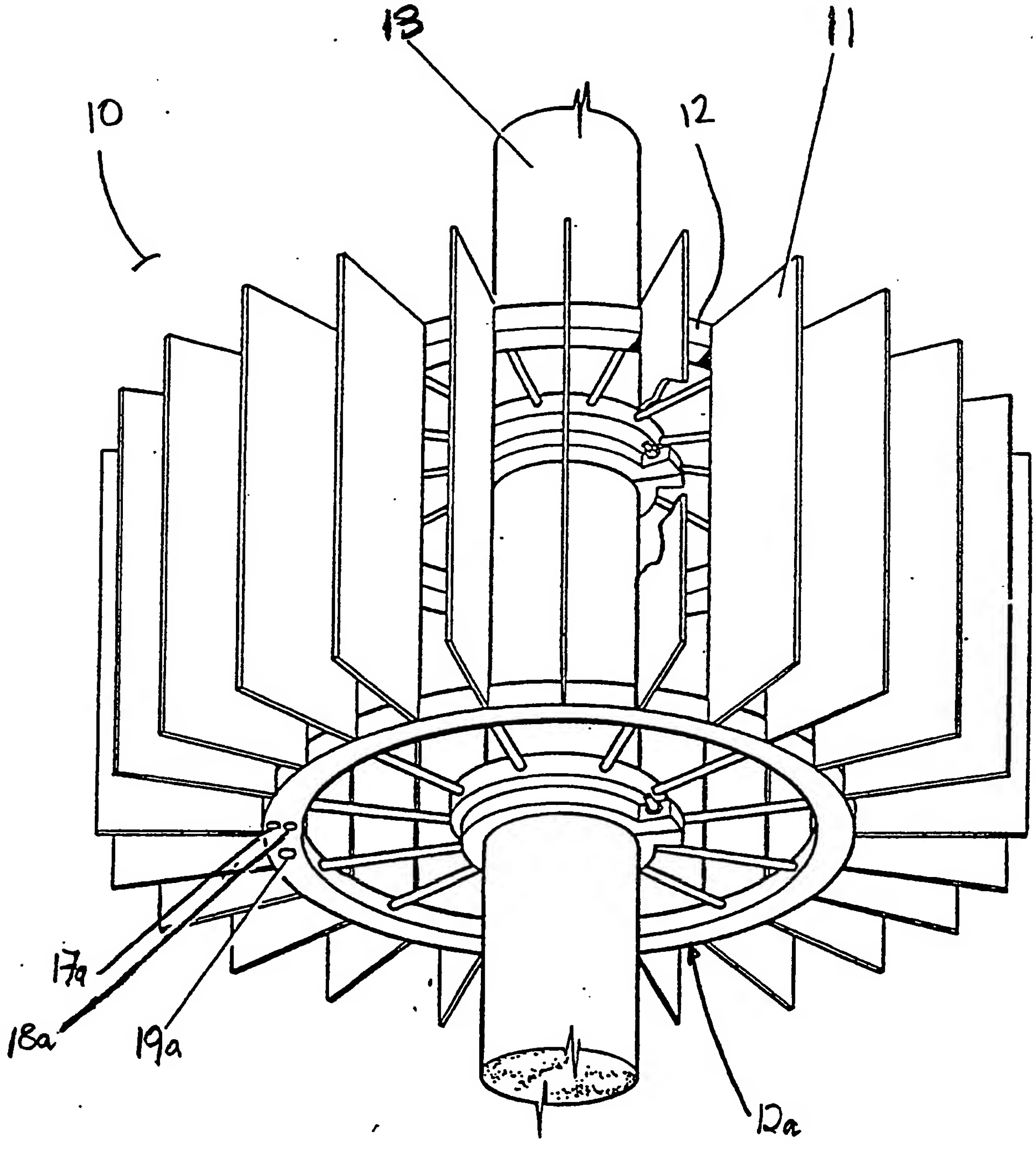

FIG. 1

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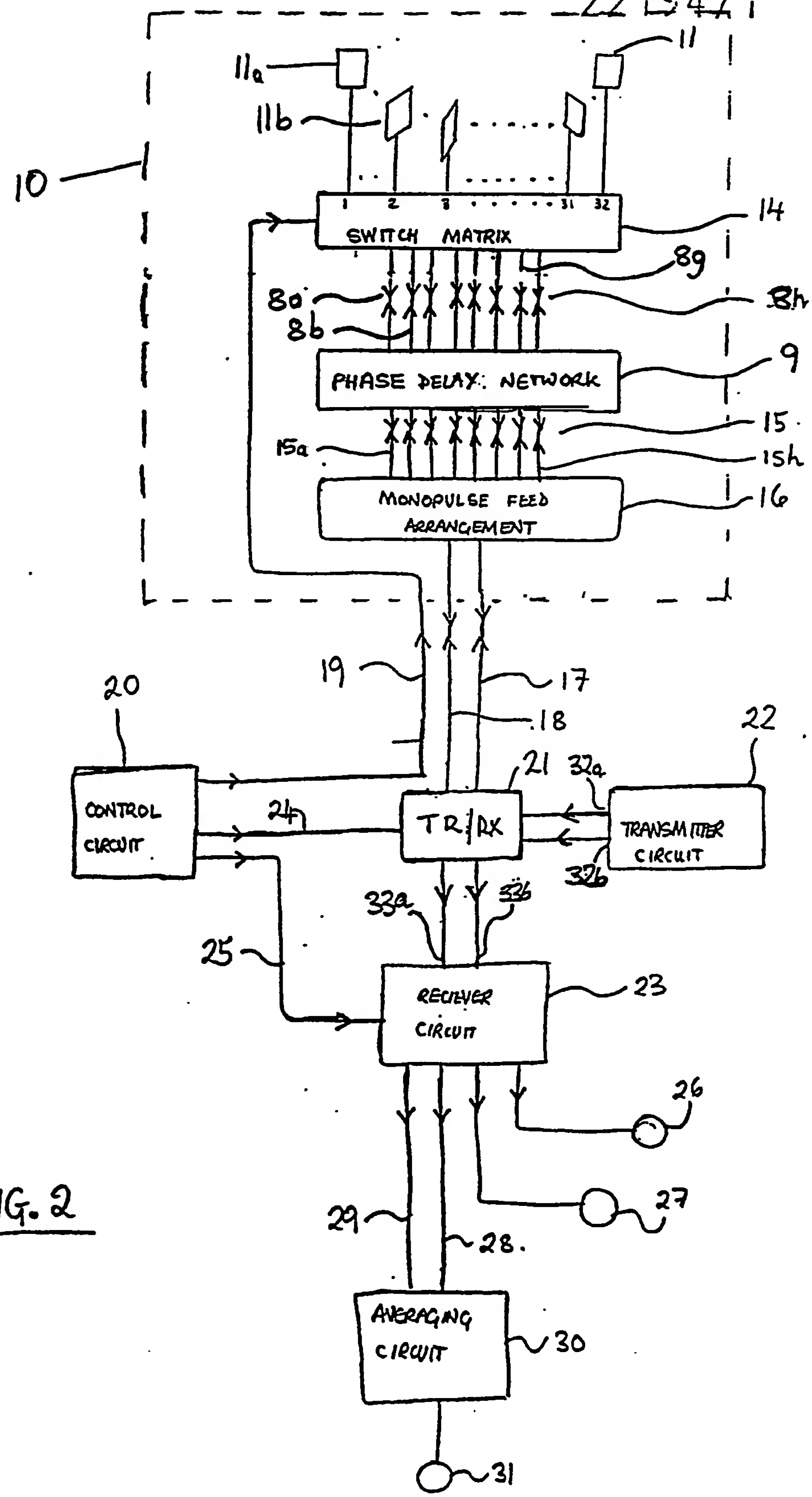

FIG. 2

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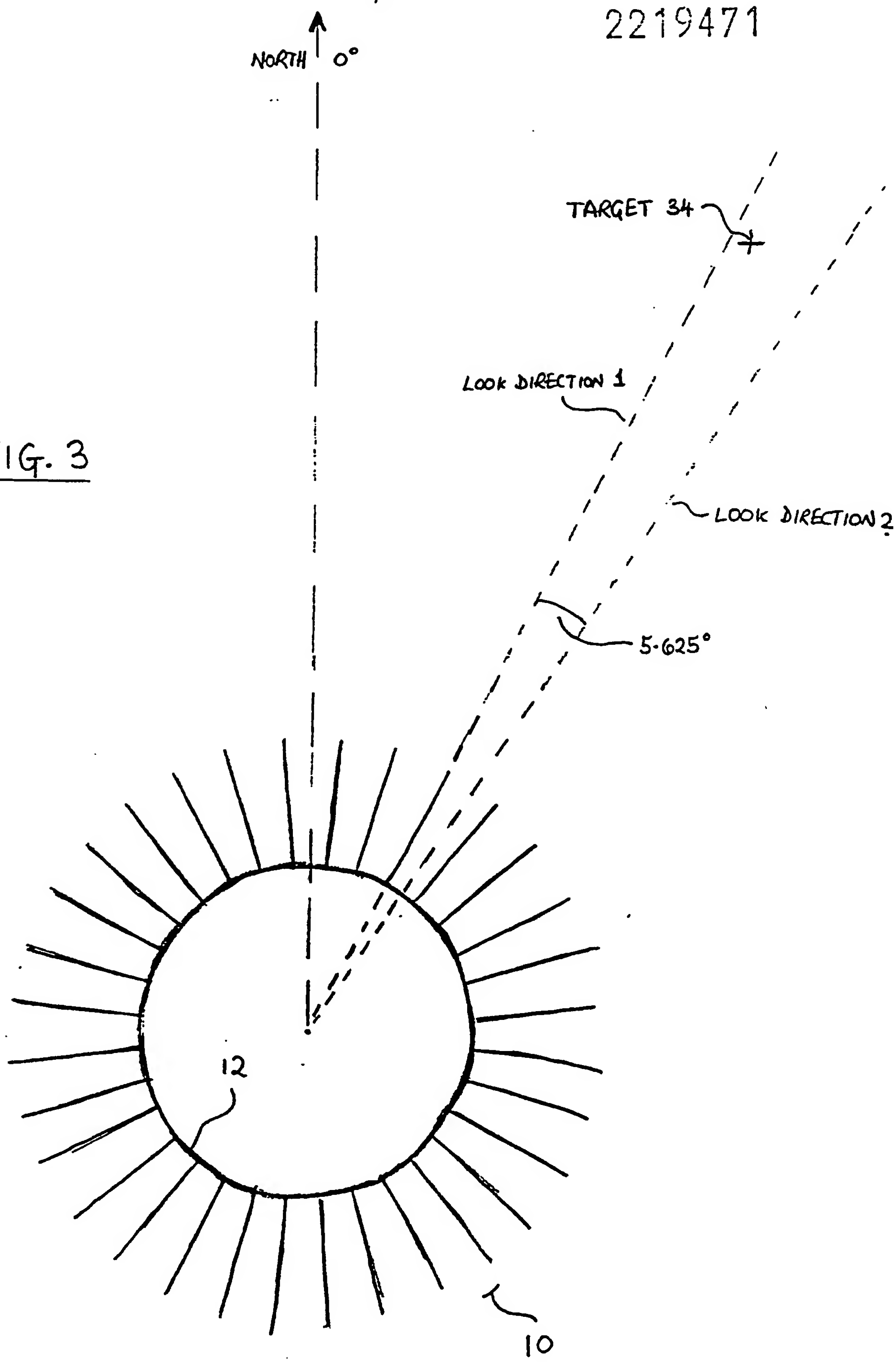

FIG. 3